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Direct rebound effect on urban residential electricity use: An empirical study in China

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ABSTRACT

Though improving energy efficiency is an important approach to decrease the energy consumption, the rebound effect caused by technology progress negatively affects the effectiveness of energy efficiency policies. This paper empirically investigates direct rebound effect of urban residential electricity use in China. Using China's 30 provincial government panel data from1996 to 2010, we build a co-integration equation and a panel error correction model to analyze the direct rebound effect. The results indicate that an obvious rebound effect in the Chinese urban residential electricity consumption does exist. Specifically, the long-term rebound effect is 0.74, while the short-term rebound effect is 0.72. Therefore, the rebound effect significantly impairs functions of energy efficiency policies. For this reason, Chinese government should take the rebound effect into consideration when formulating energy policies.

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1. Introduction

In 2010, China surpassed the U.S. as the world's biggest energy consumption country, whose total energy consumption amounted to 3.25 billion tons of standard coal, up 5.9% from 2009 and reached a new record. China accounts for about 20% of global energy consumption but less than 10% of total world GDP. Per capita energy consumption in China came close to the level of the world average, while per capita GDP is only 50% of the world average. In order to change this situation, Chinese government proposed that per unit of GDP (energy intensity) was expected to fall by 20% in 2010 compared to 2005, and actually realized by 19.06%. The Outline of the Twelfth Five-Year Plan for National Economic and Social Development of the People's Republic of China (Draft), which was issued in March 2011, also explicitly points out that China will reduce the energy consumption per unit of GDP by 16% and the carbon dioxide emission per unit of GDP (carbon intensity) by 17% during the Twelfth Five-Year Plan period.

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In order to reduce energy demand and carbon emissions, all regions and departments are seeking ways to improve energy efficiency. Many scholars also argue that enhancing energy efficiency can reduce the energy consumption [1–4]. However, can the improved energy efficiency reduce energy consumption? In reality, Chinese energy consumption still kept growing from 1996 to 2010, though energy efficiency was continuously improved during this period, see Fig. 1.

Why did this happen? In fact, rebound effect (RE) may arise due to the ignorance of the market reaction to energy efficiency, and thus the energy-efficiency policies are not as effective as people expected. Rebound effect means that the improvement of energy efficiency does not necessarily reduce energy consumption and sometimes even make energy consumption increase. As we know, the improved energy efficiency gives rise to not only a decrease in energy consumption, but also reduction in energy prices. But, lower price will increase energy consumption to some extent, and thereby cause rebound effect. The existence of this phenomenon triggers a sustained boom in the study on rebound effects. Many scholars have investigated the reasons for rebound effects in details, and put forward the corresponding policy and suggestion [5–12]. As China has been the biggest energy consumer and an important carbon emission country, most of the relevant literature has begun to investigate causality between energy consumption and economic growth as well as energy demand forecast, However, these studies overemphasized energy efficiency improvement, as a result of technological advantage and ignored other implications from the improvement, such as rebound effect, which lead to policy makers deviating from main theme. This paper will empirically deal with the issue of energy rebound effect.

Although the urban household accounted for about 10% of energy consumption during 1996–2010 in China, but electricity use increased from 11% in 1996 to 26% in 2010, (Fig. 2). This rising trend will continue as people's living standards and quality of life gradually improve. Therefore, it is necessary to investigate rebound effect of electricity consumption in urban China. This paper will use the 1996–2010 China's 30 provincial government panel data to build a co-integration equation and a panel error correction model to analyze the direct rebound effect of urban residential electricity use. Finally, based on empirical analysis, this paper will also discuss the ways to reduce energy consumption in theory.

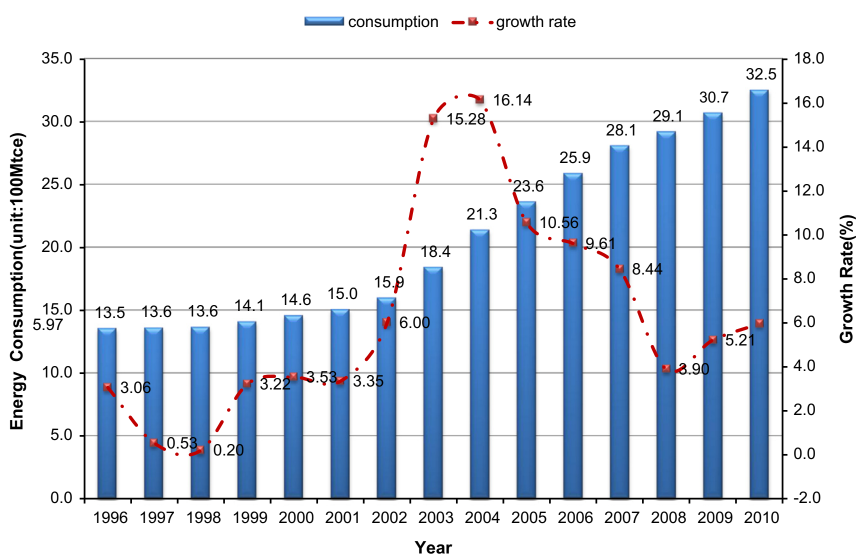


Fig. 1. Energy consumption in China from 1996 to 2010.
(Data sources from China Statistical Yearbook 2011).

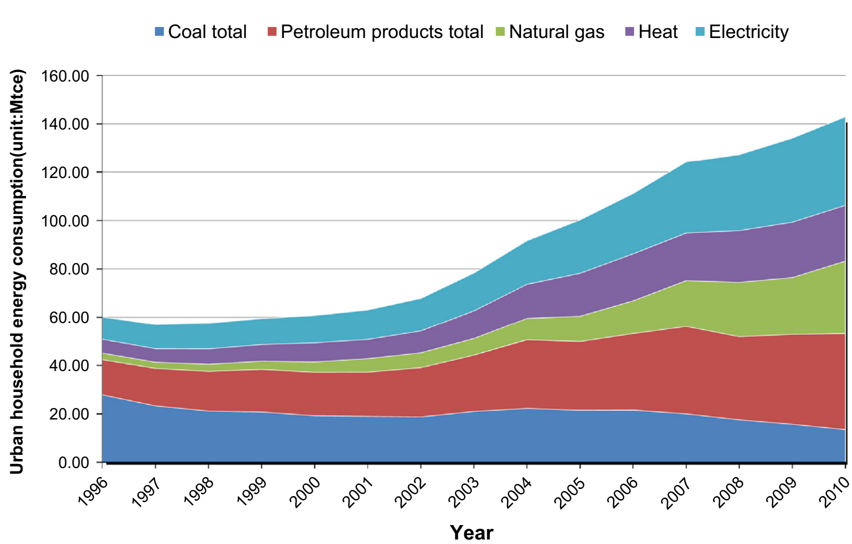


Fig. 2. Urban household energy consumption structure in China from 1996 to 2010.
(Data sources from China Energy Statistical Yearbook 1997–2011).

The content is organized as follows. Section 2 reviews the literature related to direct rebound effect. Section 3 is devoted to illustrating the econometric model and the experimental data sources. Section 4 contains our empirical analysis and results, and Section 5 presents our conclusions and policy implications.

2. Literature review

2.1. Economic mechanism

Energy rebound effect is used to describe the paradox between energy consumption and energy efficiency. Based on utility theory, Jevons first proposed this issue in his paper “The coal question”, in which the author presented the idea that it was ridiculous to reduce fuel consumption through using it economically and instead the opposite was true [13]. This is the so called “Jevons' paradox”.

Rebound effect raised widespread concern after the first oil crisis in the 1970s. Earlier research and debates about energy conservation focused on the fields of economics, environment, energy and engineering etc. Specifically, since engineering technical experts argued that improving energy efficiency could significantly reduce energy consumption, energy conservationists and environmentalists claimed that improving energy efficiency was an effective approach to reduce energy consumption, and an energy efficiency improvement could reduce energy expenditure more or less. Therefore, energy conservation should rely mainly on the efforts of science and technology. However, more scholars took the opposite view. Khazzoom pointed out that the improvements in energy efficiency could lead to the increase in the energy service demand [6]. So the actual reduction in energy consumption would not change in proportion to the reduction in energy consumption of per unit of energy service. Brookes argued that energy efficiency would lead to economic growth which would sequentially increase energy consumption [5]. This is the famous Khazzoom–Brookes Postulate, that is, when energy price remains unchanged, energy efficiency improvements caused by technological advantages will increase rather than reduce the energy consumption.

Based on the perfect market mechanism hypothesis, especially the energy market mechanism, Greening et al. divided the rebound effect mechanism into four main categories [7]:

(1) Direct effects: improved energy efficiency will decrease the effective price of an energy service and therefore lead to an increase in consumption of that service. This will offset the reduction of energy consumption caused by the advanced efficiency. The direct effect is mainly reflected in substitution effect and income effect.
(2) Economy-wide effects or market-clearing price and quantity adjustments: the energy rebound effect on the overall economy.
(3) Transformation effects: technology progress will change the consumer preferences, reform the social system and reconstruct the production organization.
(4) Secondary effects: the impact on other production/service. Energy efficiency improvement will reduce the cost of the manufacturing sector; therefore, the prices of their products will come down, which will promote the consumption. So that the manufacturing sector will increase the energy demand.

Transformation effects and secondary effects are collectively called indirect rebound effect. Due to the complexity of indirect and economy-wide effects, most of the literature studied the direct effect [12]. For the same reason, this paper will study the direct rebound effect based on the residential energy consumption.

2.2. Definition of direct rebound effect

On the basis of a single energy service or a single-department energy service, there exists several prevalent definitions of direct rebound effect, which always involves a single energy service or a single-department energy service. In order to quantitatively analyze and estimate direct rebound effects of residential energy consumption, it is necessary to identify a feasible definition. Similarly, there are several proxy variables used to measure the rebound effect, and which is practicable depends on certain conditions [14]. These definitions are summarized like the following.

Mizobuchi graphically illustrated direct rebound effects in Fig. 3:

In Fig. 3, ε_0 and $\varepsilon_1(\varepsilon_0<\varepsilon_1)$ represent different energy efficiency levels of energy service. Accordingly, rebound effect is defined as [15]:

$$\begin{aligned}\text{rebound effect (RE)} &= \frac{\text{rebound consumption}}{\text{expected savings}}\times 100\% \\ &= \frac{\text{expected savings} - \text{actual savings}}{\text{expected savings}}\times 100\% \\ &= \frac{E_2-E_1}{E_0-E_1}\times 100\% \\ &= 1-\frac{E_0-E_2}{E_0-E_1}\times 100\%\end{aligned}$$

RE of 10% means that 10% of the expected conservation is offset by the increased consumption. By comparing energy demand before and after the improvement of energy efficiency, this method can estimate the change of energy consumption. Since the changes of other factors may influence the energy consumption demand, we have to control other variables during the calculation. However, it is always very difficult to control those variables in practice. Consequently, the results from this approach are potentially biased.

Another method stems from the household production function proposed by Becker [16], in which the energy service is formulated as a function of energy consumption, time, capital and other inputs, assuming that the effectiveness of individual family comes from the energy service, such as the comfortable space temperature. Based on this framework, Wirl proposed the economic definition of energy efficiency $\varepsilon=S/E$, in which ε is defined as the ratio of useful energy service to energy inputs [17]. That is, if the energy efficiency increases, the energy consumption will decrease. So we get the price of the energy service $P_S=P_E/\varepsilon$. By means of the above concepts, many scholars have presented the most common definition of rebound effect as follows [5,18–20]:

$$RE=\eta_\varepsilon(S)=1+\eta_\varepsilon(E), \tag{1}$$

in which $\eta_\varepsilon(E)$ denotes the efficiency elasticity of energy demand, and $\eta_\varepsilon(S)$ denotes the efficiency elasticity of energy service. The energy savings caused by energy efficiency improvement are

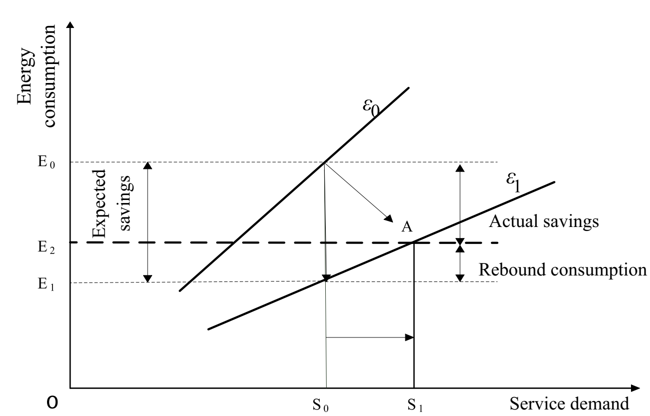


Fig. 3. Graphic of direct rebound effect.

effective only when the efficiency elasticity of demand for energy service is zero, that is, the efficiency elasticity of demand for energy is equal to minus one. A positive rebound effect implies that $\eta_\varepsilon(S) > 0, \quad |\eta_\varepsilon(E)| < 1$.

Saunders has done some specifications for the previous studies, and defined the rebound effect as follow [21–23]:

If RE > 1, the rebound effect is called backfire effects;
If RE = 1, the rebound effect is called full rebound effects;
If RE < 1, the rebound effect is called partial rebound effects;
If RE = 0, the rebound effect is called zero rebound effects;
If RE < 0, the rebound effect is called super conservation effects.

Since it is difficult to calculate ε, the energy rebound effect is often estimated from the price elasticity of energy service [18]. That is,

$$RE = \eta_\varepsilon(S) = -\eta_{P_S}(S) \tag{2}$$

Some other scholars have estimated the rebound effect in this way which is easier to implement than Eq. (1) [6,24,25]. However, this definition is mainly based on two hypotheses:

(1) Symmetry: consumers respond in the same way to energy price decline and energy efficiency improvement.
(2) Exogeneity: energy prices' change can't affect energy efficiency. That is, $\eta_{P_E}(\varepsilon) = \partial \ln \varepsilon / \partial \ln P_E = 0$.

In this method, symmetry plays a critical role. The direct changes in price have a greater effect on the improvement of production efficiency. When the time series are stationary, the decline in energy prices will not affect the energy efficiency. However, the rising energy prices will promote the technology progress. Exogeneity means that energy efficiency may affect energy costs, and vice versa. This can be proved by empirical analysis of the co-integration relationship through the introduction of instrumental variables in simulation model.

Due to data accessibility, Eq. (2) is employed more widely than Eq. (1) to estimate the direct rebound effect. Similarly, data on energy consumption is more available and more accurate than data on energy services. Since $P_S = P_E/\varepsilon$, if energy efficiency ε is regarded as a constant, then the definition of the rebound effect can be achieved by transforming the price elasticity of energy consumption [22,26,27]. That is:

$$RE = \eta_\varepsilon(S) = -\eta_{P_E}(E) \tag{3}$$

Analogous to Eqs. (2) and (3) is also based on the symmetry and exogeneity hypotheses. That is, in order to get rebound effect of residential energy consumption, we only need to calculate the elasticity of energy consumption with respect to the price of the energy.

Khazzoom argued that the empirical analysis of direct rebound effect would be limited to micro-economic level [6]. At this level, the technology progress will reduce the energy consumption, and in turn, the rising price of energy will affect the energy efficiency. Many economists use the price elasticity of energy consumption as instrumental variables to estimate the rebound effect. Hass and Biermayr argued that when the energy efficiency is unavailable, the price elasticity of energy consumption could be calculated by constant elastic demand dynamic standard function in double-logarithmic form [15]. Due to the availability and accuracy of data, this paper tends to use the price elasticity of energy consumption to estimate the energy rebound effect.

3. Methodology and data

3.1. Econometric model and variables

This paper aims to estimate the long-term and short-term rebound effect of Chinese urban residential electricity consumption. Based on the work by Haas and Biermayr [15], we add the population as a new variable P_{it} into the econometric model.The revised econometric model is written as follows:

$$\ln E_{it} = \alpha + \beta_1 \ln I_{it} + \beta_2 \ln P_{E_{it}} + \beta_3 \ln P_{it} + \beta_4 \ln DD_{it} + \mu_{it}, \tag{4}$$

in which α is a constant, $\beta_1 - \beta_4$ are the parameters to be estimated, and μ_{it} represents the random error term. Then a simple explanation of the variables in the model equation is given as follows.

E_{it}: the explanatory variable, indicating the electricity consumption of the province i in year t of the urban residents (unit: *KWH*).

I_{it}: per capita disposable real income of the province i in year t of the urban residents (unit: Yuan). It is calculated through numerical manipulation in which the nominal per capita disposable income value is reduced according to the urban consumer price index (1995 as the base period) of the corresponding year in the region and the regional price difference. Price difference is described by the purchasing power parity of all the provinces of China in the period from 1996 to 2010, which refers to Brandt and Holz's research results of the regional purchasing power parity of China in 2000 [28]. Generally, the real per capita disposable income reflects the residents' living standard in the region. The improvement of living standard has brought the increase of new family power consumption equipment and the rise of household electricity consumption. On the other hand, it promotes the process of replacing the old electric equipment with low energy efficiency and greatly reduces the residents' electricity consumption.

$P_{E_{it}}$: residential electricity prices of the province i in year t. The residential electricity price is calculated according to the urban consumer price index, and the purchasing power parity of the Chinese provinces derived by following the logic of Brandt and Holz [15]. Because it is difficult to obtain the residential electricity prices in various regions of China, this study selects the civil electricity price of all capital cities as a replacement. There much more substitutability exists in the household energy consumption. Intuitively, the rise of the residential electricity price has a negative impact on the residential electricity consumption.

P_{it}: the population of the province i in year t. Since a human being is the main body of energy consumption, the greater the population, the greater the need there is for electrical equipments and electricity consumption.

DD_{it}: the degree day value of the province i in year t. Due to the diversities of latitude and geographical conditions in various regions of China, the climate is very different, which has a large effect on the electricity consumption of a region especially in winter and summer. Generally, the regions with a larger degree day value have a bigger demand for electricity consumption. In the early 1950s, Thom HC explored the relationship between energy consumption and temperature using the degree day method for the first time [29]. The degree day of a day refers to the actual deviation between daily average temperature and the prescribed base temperature. The degree day can be divided into two types, the heating degree day and the cooling degree day [30]. The annual heating degree days refers to the number of accumulated temperature when the daily average temperature is lower than the base temperature in a year. The annual cooling degree days refers to the number of accumulated temperature when the daily average temperature is higher than the base temperature in a year. The corresponding

formula is given by

$$\begin{cases} HDD = \sum_{i=1}^{n}(1-rd)(T_{b1}-T_i) \\ CDD = \sum_{i=1}^{n} rd(T_i-T_{b2}) \end{cases}, \quad (5)$$

in which HDD is the value of heating degree days of a particular year; CDD is the value of cooling degree days of a particular year; n is the number of days a particular year; T_i represents the daily average temperature; T_{b1} is the base temperature of the heating degree day; T_{b2} is the base temperature of the cooling degree day; if daily average temperature is higher than the base temperature, then $rd=1$, otherwise, $rd=0$ [31]. Because this method demands a heavy workload and the required data is not readily available, the study improves the method proposed by Wayne by calculating the degree days of a year as follows:

$$\begin{cases} HDD = \sum_{m=1}^{12}(1-rd)(T_{b1}-T_m)M \\ CDD = \sum_{m=1}^{12} rd(T_m-T_{b2})M \end{cases}, \quad (6)$$

in which T_m represents the monthly average temperature; m is the number of days in a month; $rd=1$, if monthly average temperature is higher than the base temperature; otherwise, $rd=0$. The degree days' value in a particular year is:

$$DD = HDD + CDD$$

Because it is hard to acquire the data of daily average temperature in various regions of China, this study selects the temperatures in the capital cities as a replacement. By doing so, besides the availability of the data, this method considers the other two reasons: (1) within the same province, latitude and geographical conditions are usually similar, climate differences and temperature changes are small; (2) capital city is usually the largest city of the province, and has the largest population.

When we use the above method to estimate price elasticity, the premise is a price decline. However, the price is fluctuating. In order to solve this problem, Dargay and Gately put forward a method which can reflect the rise and fall of energy prices [32,33], which the price change is broken down into three parts: $P_{E_{it}}^{max}$(the highest price in history), $P_{E_{it}}^{cut}$ (prices fall), and $P_{E_{it}}^{rec}$ (price recovery). In order to use this method in the logarithmic function, Haas and Biermayr made some changes from Dargay and Gately's decomposition method [15], and the pertinent definition is as follows:

$$P_{E_{it}} = P_{E_{it}}^{max} P_{E_{it}}^{cut} P_{E_{it}}^{rec}, \quad (7)$$

in which, $P_{E_{it}}^{max} = max\{P_{E_{i1}}, P_{E_{i2}}, ..., P_{E_{it}}\}$, $P_{E_{it}}^{cut} = \prod_{m=0}^{t} \min\{1, ((P_{E_{im-1}}^{max}/P_{E_{im-1}})/(P_{E_{im}}^{max}/P_{E_{im}}))\}$, and $P_{E_{it}}^{rec} = \prod_{m=0}^{t} max\{1, ((P_{E_{im-1}}^{max}/P_{E_{im-1}})/(P_{E_{im}}^{max}/P_{E_{im}}))\}$

For example, Fig. 4 depicts the decomposition of the average residential electricity of China from 1996 to 2010.

Taking logarithmic on both sides of Eq. (7) yields:

$$\ln P_{E_{it}} = \ln P_{E_{it}}^{max} + \ln P_{E_{it}}^{cut} + \ln P_{E_{it}}^{rec} \quad (8)$$

Inserting Eq. (8) into Eq. (4) gives

$$\ln E_{it} = \alpha + \beta_1 \ln I_{it} + \beta_2^{max} \ln P_{E_{it}}^{max} + \beta_2^{cut} \ln P_{E_{it}}^{cut} + \beta_2^{rec} \ln P_{E_{it}}^{rec} + \beta_3 \ln P_{it} + \beta_4 \ln DD_{it} + \mu_{it}, \quad (9)$$

in which β_2^{cut} (coefficient of $\ln P_{E_{it}}^{cut}$) stands for the long-term rebound effect.

3.2. Data sources

Under the framework of the Eq. (9), we use a panel data to estimate direct rebound effect of urban residential electricity consumption. Considering the consistency and availability of statistical data, Tibet, Taiwan, Hong Kong and Macao are not included in this study. The data include the urban residential electricity consumption, the per capita disposable income of urban residents, the average temperature of winter and summer, the residential electricity price and urban population. Specifically, the data of the per capita disposable income of urban residents and the average temperature of winter and summer in various provinces are collected from China Statistical Yearbook (1997–2011). The data of the residential electricity price in various provinces are collected from China Price Yearbook (1997–2011). China Energy Statistical Yearbook (1997–2011) provides the data of the urban residential electricity consumption, and the data of urban population in various provinces come from the China Population Statistical Yearbook (1997–2011). We described variables of this study in Table 1.

4. Econometric results and analysis

4.1. Panel unit root test

There are many methods for panel unit root test and each of them has its own uniqueness. Therefore, it is difficult to get the

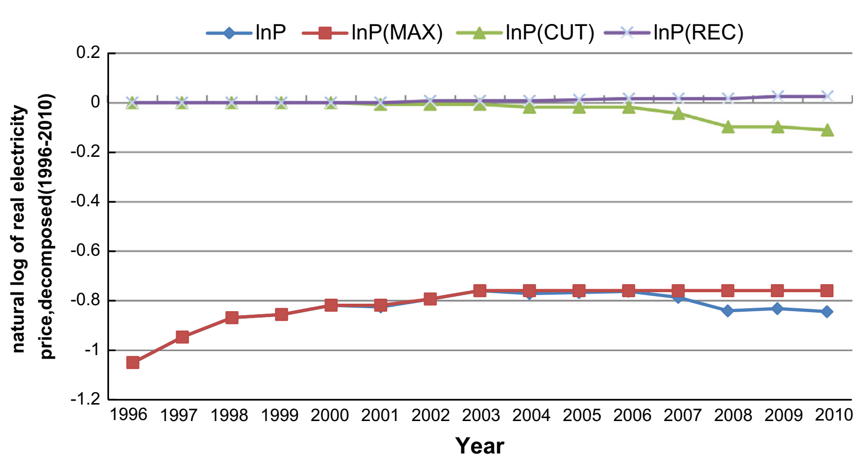


Fig. 4. Decomposition of the Logarithm of Price.
(Data sources from China Statistical Yearbook 1997–2011).

same conclusion with different test methods. In order to guarantee the results' robustness and improve the credibility of the conclusion, this paper use LLC (Levin–Lin–Chu) test, IPS (Im–Pesaran–Shin) test and CH (Ch-statistics) test method to test panel unit root of each variable. (Panel unit root test results are shown in Table 2). Except for the lnP_E^{max} and ln *DD*, the other variables do not refuse the null hypothesis of existing panel unit root, but there does not exist panel unit root for the first order difference of all variables. The result of the three unit root test shows that all variables of the regression model are integrated order 1.

4.2. Panel co-integration test

In applied economics, if the regression model are not cointegrated, the parameter estimates and corresponding test statistics would be biased and inconsistent [34]. From panel unit root test in Table 2, all variables in the model are single integrated order series, and fulfill the requirements of the panel co-integration test and can continue the panel co-integration test. Panel PP, Panel ADF, Group PP and Group ADF refuse the null hypothesis of the existence of no co-integration relationship at the 5% significant level, while the Panel v, Panel rho and Group rho can't refuse the null hypothesis, see Table 3. Considering the sample period in this empirical study was only 15 years, we argue that there exist co-integration relationships among the variables. And the Kao test also refuses the null hypothesis of no co-integration [35], which further supports the conclusion of the existence of co-integration relationships among the variables. Then, this study takes the Engle and Granger (EG) two-step method to estimate the long-term equilibrium equation (the co-integration equation) [36]. According to correlated random effects (Hausman-test) (Table 4) and redundant fixed effects test (*F*-test) (Table 5), we argued that cross-section fixed effect model is the optimal estimation model, so we do a cross-sectional fixed effect regression. Finally, through the least squares estimation, we get the long-term equilibrium equation. The results of cross-section fixed effects regression are shown in Table 6.

According to the value of adjusted R-squared and F-statistics, we can conclude the whole long term co-integration model fit very well. *DW* of 1.591550 also means there is no self-correlativity

Table 3
Results of panel co-integration test.

	Statistics	With no trend	With trend
Pedroni test	Panel v-statistic	−2.541749 (0.9945)	−4.775044 (1.0000)
	Panel rho-statistic	4.865800 (1.0000)	5.647109 (1.0000)
	Panel PP-statistic	−10.88599 (0.0000)	−9.423157 (0.0000)
	Panel ADF-statistic	−10.66998 (0.0000)	−6.905713 (0.0000)
	Group rho-statistic	7.539132 (1.0000)	
	Group PP-statistic	−19.45867 (0.0000)	
	Group ADF-statistic	−8.516581 (0.0000)	
Kao test	ADF-statistic	−4.614029 (0.0000)	

Table 4
Correlated Random Effects-Hausman Test.

Test Summary	Chi-Sq.Statistic	Chi-Sq.d.f.	Prob
Test cross-section random effects			
Cross-section random	72.770794	6	0.0000

Table 1
Descriptive statistics of the variables.

	ln *E*	ln *I*	ln P_E^{max}	ln P_E^{cut}	ln P_E^{rec}	ln *P*	ln *DD*
Mean	21.97262	8.926846	−0.870070	−0.109913	0.062704	16.39359	6.240279
Media	22.06089	8.906552	−0.865091	−0.080506	0.042135	16.47929	6.316261
Maximum	24.23242	9.942893	−0.562372	0.000000	0.256087	17.96560	7.894765
Minimum	19.03587	8.107055	−1.534299	−0.494187	0.000000	14.15754	2.517696
Std. Dev.	0.943331	0.411836	0.184481	0.096155	0.059636	0.778458	1.014122
Skewness	−0.581245	0.185824	−0.607826	−1.164319	1.267165	−0.920153	−1.501900
Kurtosis	3.283733	2.281536	2.985691	4.304400	4.194568	3.844630	5.989308
Observations	450	450	450	450	450	450	450
Cross sections	30	30	30	30	30	30	30

Table 2
Results of panel unit root test.

Variable	LLC test	IPS test	CH test	
			ADF-Fisher	PP-Fisher
ln *E*	2.49782 (0.9938)[b]	7.10510 (1.0000)	19.7053 (1.0000)	25.2762 (1.0000)
Δ ln *E*[a]	−17.1743 (0.0000)	−15.3238 (0.0000)	306.603 (0.0000)	407.616 (0.0000)
ln *I*	3.90261 (1.0000)	10.6106 (1.0000)	8.13534 (1.0000)	14.7752 (1.0000)
Δ ln *I*	−12.3338 (0.0000)	−10.4638 (0.0000)	212.986 (0.0000)	268.107 (0.0000)
ln P_E^{max}	−2.65676 (0.0039)	−10.3790 (0.0000)	150.293 (0.0000)	195.449 (0.0000)
Δ ln P_E^{max}	−9.03794 (0.0000)	−13.0427 (0.0000)	206.791 (0.0000)	186.239 (0.0000)
ln P_E^{cut}	6.41257 (1.0000)	11.0828 (1.0000)	8.48944 (1.0000)	11.2667 (1.0000)
Δ ln P_E^{cut}	−13.8670 (0.0000)	−9.80560 (0.0000)	212.933 (0.0000)	253.711 (0.0000)
ln P_E^{rec}	−5.29377 (0.0000)	0.73324 (0.7683)	51.634 (0.7706)	84.0129 (0.0221)
Δ ln P_E^{rec}	−18.6206 (0.0000)	−13.5418 (0.0000)	265.528 (0.0000)	310.433 (0.0000)
ln *P*	−2.73878 (0.0031)	5.22259 (1.0000)	38.6405 (0.9855)	69.0028 (0.1993)
Δ ln *P*	−9.08932 (0.0000)	−7.56879 (0.0000)	166.179 (0.0000)	164.466 (0.0000)
ln *DD*	−12.1265 (0.0000)	−11.3941 (0.0000)	241.233 (0.0000)	299.799 (0.0000)
Δ ln *DD*	−22.2490 (0.0000)	−20.4152 (0.0000)	395.457 (0.0000)	640.295 (0.0000)

[a] Δ represents the first-order difference.
[b] The value in the brackets is *P* value.

for residuals series. We further test unit root of the residuals series by the four kinds of testing method, and all results refuse the null hypothesis of existing panel unit root in the 5% significant level. This means that the origin of residual series is stationary series, (Table 6). Therefore, the results from EG two step test method also suggest that a co-integration relationship exist among the variables.

4.3. Testing the exogeneity of the price variable

Microeconomic theory indicates that the price of any good is a function of the supply of this good in the marketplace (keeping demand constant).Furthermore, the demanded amount is determined by the market price,vice versa the good demanded also affect the market price. As a result, it is difficult to identify the direction of the causality for many goods, i.e., whether demand affects price or price affects demand. In such condition, we can assume the price is an endogenous explanatory variable, and thus we can use the Hausman test to demonstrate the exogeneity of price in Eq. (4) [37]. In this paper we take the one-period lag logarithm of price ($\ln P_{E_{it-1}}$) and its logarithm square ($\ln^2 P_{E_{it-1}}$) as the instrument variables. And take the endogenous variable $\ln P_{E_{it}}$ as the dependent variable, and the other exogenous explanatory variables and instrument variables of Eq. (4) as explanatory variables of the linear regression. According to the test of correlation, the test of significance of linear regression and the test of significance of regression coefficients, the instrument variables and endogenous variables are proved to be highly correlated. (the value of the F-statistics is 93.08730). After finding the instrumental variables satisfying the dependency and the exogeneity, we make a linear regression for the other explanatory variables and the instrument variables ($\ln P_{E_{it-1}}$, $\ln^2 P_{E_{it-1}}$). Then we extract the residual $\hat{\mu}$, and do a new linear regression by putting $\hat{\mu}$ to Eq. (4). The T-value of $\hat{\mu}$ is 3.842165 which is significant in the 5% significant level. Therefore, we confirm the price variable is endogenous [38].

Table 5
Redundant fixed effects test.

Effects test	Statistic	d.f.	Prob
Test cross-section fixed effects			
Cross-section F	13.298820	(29,414)	0.0000
Cross-section Chi-square	296.247559	29	0.0000

4.4. Panel error correction model (PECM)

Error correction model (ECM) is often used to estimate short-term elasticity. ECM is a specific econometrics model, which uses a long-term co-integration equation as an instrument variable to solve the spurious regression problem. In this study, the short-term price elasticity of the ECM is the short-term energy rebound effect which we want to obtain.

According to panel co-integration analysis, we find that there is a long-term equilibrium relationship between the dependent variable (urban residential electricity consumption in China) and each explanatory variables (e.g. the per capita disposable income of urban residents). In order to offset the deficiency of the long-term statistical model, we construct a short-term dynamic model to reflect the correction mechanism for the short-term equation deviating from the long-term one. So according to Eq. (9) and Table 6, we can obtain the residual series $\hat{\mu}_{it}$ as follows:

$$\hat{\mu}_{it} = ecm_{it} = \ln E_{it} - \hat{\alpha} - \hat{\beta}_1 \ln I_{it} - \hat{\beta}_2^{max} \ln P_{E_{it}}^{max} - \hat{\beta}_2^{cut} \ln P_{E_{it}}^{cut} - \hat{\beta}_2^{rec} \ln P_{E_{it}}^{rec} - \hat{\beta}_3 \ln P_{it} - \hat{\beta}_4 \ln DD_{it},$$

and take it as an error correction. Then the short-term estimations are obtained through error correction model (ECM) as depicted by Eq. (10):

$$\Delta \ln E_{it} = \gamma_1 \Delta \ln I_{it} + \gamma_2 \Delta \ln P_{E_{it}}^{max} + \gamma_3 \Delta \ln P_{E_{it}}^{cut} + \gamma_4 \Delta \ln P_{E_{it}}^{rec} + \gamma_5 \Delta \ln P_{it} + \gamma_6 \Delta \ln DD_{it} + \gamma_7 \Delta \ln E_{it-1} + \gamma ecm_{it-1} + \varepsilon_{it}, \tag{10}$$

in which the value of γ_3 (coefficient of $\Delta \ln P_{E_{it}}^{cut}$) is the short-term rebound effect, and ε_{it} is random error. Eq. (10) shows that the short-term volatility of urban residential electricity consumption in China not only depends on various factors' short-term changes but also is influenced by the deviation from long-term equilibrium in previous period (ecm_{it-1}). In addition, the difference series reflect the volatility of the variable; for example, $\Delta \ln I_{it}$ shows the volatility of the per capita disposable income of urban residents, and $\Delta \ln P_{E_{it}}$ shows the volatility of household electricity price. The coefficient of difference series means the short-term elasticity.

The long-term co-integration panel model estimated with ordinary least squares method is:

$$\ln E_{it} = 8.17 + 0.95 \ln I_{it} - 0.08 \ln P_{E_{it}}^{max} - 0.74 \ln P_{E_{it}}^{cut} + 0.67 \ln P_{E_{it}}^{rec} + 0.26 \ln P_{it} + 0.14 \ln DD_{it} + \mu_{it}.$$

After establishing the model, we can use error correction model to estimate the short-term rebound effect of urban residential electricity use in China. We firstly do a co-integration regression

Table 6
Estimation of long co-integration equation and unit root test of residual series.

Estimation model				Residual series unit root test		
$\ln E_{it} = \alpha + \beta_1 \ln I_{it} + \beta_2^{max} \ln P_{E_{it}}^{max} + \beta_2^{cut} \ln P_{E_{it}}^{cut} + \beta_2^{rec} \ln P_{E_{it}}^{rec} + \beta_3 \ln P_{it} + \beta_4 \ln DD_{it} + \mu_{it}$						
Variable	Coefficient	t-Statistic	Prob.	Test method	Statistic	Prob
$\ln I_{it}$	0.947757	20.40914	0.0000	LLC test	−4.74502[a]	0.0000
$\ln P_{E_{it}}^{max}$	−0.079360	−0.853581	0.3938	IPS test	−4.09720[a]	0.0000
$\ln P_{E_{it}}^{cut}$	−0.741594	−5.009917	0.0000	ADF-Fisher test	119.251[a]	0.0000
$\ln P_{E_{it}}^{rec}$	0.670163	3.346687	0.0009	PP-Fisher test	124.998[a]	0.0000
$\ln P_{it}$	0.261263	4.574507	0.0000			
$\ln DD_{it}$	0.138698	5.669505	0.0000			
c	8.170993	9.977485	0.0000			
Adjusted R-squared	0.984765					
Durbin–Watson stat.	1.591550					
F-statistic	830.2236					

[a] means that the statistic result refuse the null hypothesis of existing panel unit root.

Table 7
Results of the panel error correction model estimation.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$\Delta\ln I_{it}$	0.870367	0.077794	11.18808	0.0000
$\Delta\ln P_{E_{it}}^{max}$	0.338731	0.104247	3.249313	0.0013
$\Delta\ln P_{E_{it}}^{cut}$	−0.724889	0.171297	−4.231771	0.0000
$\Delta\ln P_{E_{it}}^{rec}$	0.161346	0.214104	0.753587	0.4516
$\Delta\ln P_{it}$				
	0.080002	0.013760	5.813943	0.0000
$\Delta\ln E_{i,t-1}$	0.031320	0.043956	0.712531	0.4766
ecm_{it-1}	−0.401446	0.040157	−9.996833	0.0000
Weighted statistics				
R-squared	0.188561	Mean dependent var.	0.170509	
Adjusted R-squared	0.173691	S.D. dependent var.	0.177143	
S.E. of regression	0.146741	Sum squared resid.	8.225615	
F-statistic	3.673759	Durbin-Watson stat.	2.049597	
Prob (F-statistic)	0.000000			

by using $\ln E_{it}$, $\ln I_{it}$, $\ln P_{E_{it}}^{max}$, $\ln P_{E_{it}}^{cut}$, $\ln P_{E_{it}}^{rec}$, $\ln P_{it}$, and $\ln DD_{it}$, and then take the stationary residual error series ecm_{it} as the error correction series establish the error correction model as follows (Table 7):

$$\Delta\ln E_{it} = 0.87\Delta\ln I_{it} + 0.34\Delta\ln P_{E_{it}}^{max} - 0.72\Delta\ln P_{E_{it}}^{cut} + 0.16\Delta\ln P_{E_{it}}^{rec} + 0.19\Delta\ln P_{it} + 0.08\Delta\ln DD_{it} + 0.03\Delta\ln E_{i,t-1} - 0.40 ecm_{it-1} + \varepsilon_{it}$$

The coefficients value of ecm_{it-1} shows the speed of adjustment to reach the co-integration equilibrium at current period. The coefficient values of ecm_{it-1} is -0.40. Adjustment value has the statistical significances at 1% levels. These results lead to estimations of direct rebound effect of 72% in the short term and of 74% in the long term for all energy services that use electricity in households. An increase in energy efficiency of these energy services potentially would bring about savings in electricity consumption of 10. This actually produces savings of 2.8 in the short term and of 2.6 in the long term. The results are more than 0 but less than 1, which means that the urban residential electricity use in China exist a partial rebound effects.

5. Conclusion and policy implication

The main objective of this paper was to provide an estimation of the direct rebound effect for all energy services that consume electricity in urban households in China. Our empirical results reveal the existence of direct rebound for residential electricity use in urban China, with its long-term rebound effect being 0.74 and short-term rebound effect 0.72. There are no back-fire effects, but only partial rebound effects. This means that, though it did not achieve the expected earnings when urban residents improved the efficiency of electricity consumption, it can still be a correct policy. If there were no energy efficiency improvement, more energy would be spent. From the saving energy viewpoint, since the technology and policy of improving energy efficiency is not as effective as we expected in theory, they cannot always be regarded as the only means to realizing the energy saving or solving the energy problems. So it cannot take the technological progress as the only approach to improve energy efficiency to achieve the energy saving or solve the energy problems. In addition, the empirical results indicate that, regardless of long-term or short-term, the elasticity of energy consumption with respect to price drop is greater than that with respect to the price rise, which are totally different from the results from Dargay and Gately and Haas and Schipper [39,40].This could be caused by the rapid growth of China's economy, the rise in urban disposable incomes, and cheaper electricity in China. People hope to get a more comfortable way of living through the electricity consumption, and the frequent use of home appliances will increase. This may lead people response to the electricity price decline more quickly and effectively than electricity price rise.

The direct rebound effect in this paper may be overestimated or underestimated. Overestimation is due to two reasons: One is the exogenous hypothesis of energy efficiency (i.e., energy efficiency is unaffected by energy prices). However, according to symmetry, consumers react in the same way to the decline in the energy electricity price as to the improvement of energy efficiency. However, this hypothesis is necessary for estimating energy direct rebound effect through energy price elasticity of energy demand. On the other hand, since China is in the high-speed economic development stage, the acceleration of urbanization and residents' disposable income will speed up the rising demand for energy, which may offset the energy savings from the improvement of energy efficiency. Underestimation can be attributed to the relationship between the direct rebound effect and capital cost. If the cost of new efficient equipment is lower than that of the old inefficient one, it may enlarge rebound effect [19,20].

To sum up, the magnitude of rebound effect should be an alterative criterion for efficiency estimation of a single energy service. Compared with developed countries, the direct rebound effect of urban residential electricity use in China is significantly higher. The main reason is that China is accelerating urbanization process and upgrading resident consumption stage. The main contribution of this paper is to evaluate the implementation effect of energy efficiency improvement project by estimating the rebound effect. When the government makes energy policy, attention should be placed not only on the increase in energy efficiency, but also on the technology subsidies to the enterprises improving the household appliance products' energy efficiency, which will help cut residential energy consumption and make energy conservation and emissions reduction more fruitful. Additionally, Chinese government should get rid of the obstruction from middle income earners to implement the tiered electricity price (TEP) reform and make consumers fully aware of the electricity cost and the scarcity of available resources [41]. Only in this way can we jump out of the “prisoner's dilemma” in the situation of low present energy price and low energy efficiency, and lead the lifestyle to a sustainable direction. Moreover, the relationship among energy prices controlled by the government, external cost of energy consumption and residential energy consumption needs to be discussed in a further research.

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References

[1] Weizsacker E, von, Lovins AB, Lovins LH. Factor Four: Doubling Wealth, Halving Resource Use. London: Earthscan; 1997.
[2] World Energy Council. Energy Efficiency Policies around the World: Review and Evaluation. London: World Energy Council; 2008.

[3] Bosseboeuf D, Chateau B, Lapillonne B. Cross-country comparison on energy efficiency indicators: the on-going European effort towards a common methodology. Energy Policy 1997;25(9):673–82.
[4] Patterson MG. What is energy efficiency? Concepts, indicators and methodology issues Energy Policy 1996;24(5):377–90.
[5] Brookes LG. Energy policy, the energy price fallacy and the role of nuclear energy in the U.K. Energy Policy 1978;6:94–106.
[6] Khazzoom JD. Economic implications of mandated efficiency in standards for household appliances. Energy Journal 1980;1(4):21–40.
[7] Greening LA, Greene DL, Difiglio C. Energy efficiency and consumption—the rebound effect—a survey. Energy Policy 2000;28:389–401.
[8] Greening LA, Greene DL. Energy use, technical efficiency, and the rebound effect: a review of the literature. Oak Ridge TN: Center for Transportation Analysis; 1998.
[9] Saunders HD. Does predicted rebound depend on distinguishing between energy and energy service? Energy Policy 2000;28:497–500.
[10] Bentzen J. Estimating the rebound effect in U.S. manufacturing energy consumption. Energy Economics 2004;26:123–34.
[11] Jin SH. The effectiveness of energy efficiency improvement in a developing country: rebound effect of residential electricity use in South Korea. Energy Policy 2007;35:5622–9.
[12] Sorrell S, Dimitropoulos J. The rebound effect: microeconomic definitions, limitations and extensions. Ecological Economics 2008;65:636–49.
[13] Jevons W.S. The coal question: can Britain survive? In: Flux, A.W., (editor). The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines. New York: Augustus M. Kelley.
[14] Mizobuchi K. An empirical study on the rebound effect considering capital costs. Energy Economics 2008;30:2486–516.
[15] Haas R, Biermayr P. The rebound effect for space heating: empirical evidence from Austria. Energy Policy 2000;28:403–10.
[16] Becker GS. A theory of the allocation of time. Economic Journal 1965;75:493–517.
[17] Wirl F. The Economics of Conservation Programs. London: Kluwer Academic Publishers; 2009.
[18] Berkhout PHG, Muskens JC, Velthuisjen JW. Defining the rebound effect. Energy Policy 2000;28:425–32.
[19] Dimitropoulos J, Sorrell S The rebound effect: microeconomic definitions, extensions and limitations. In: Proceedings of the 29th IAEE international conference, Potsdam, Germany 2006.
[20] Sorrel S. The Rebound Effect: An Assessment of the Evidence For Economy-Wide Energy Savings From Improved Energy Efficiency. UK Energy Research Center (UKERC); 2007. ⟨www.ukerc.ac.uk⟩ (Review of evidence for the rebound effect).
[21] Saunders HD. The Khazzoom–Brookes postulate and neoclassical growth. The Energy Journal 1992;13(4):131.
[22] Saunders HD. A calculator for energy consumption changes arising from new technologies. Topics in Economic Analysis and Policy 2005;5(1):1–31.
[23] Saunders HD. Fuel conserving (and using) production function. Energy Economics 2008;30:2184–235.
[24] Binswanger M. Technological progress and sustainable development: what about the rebound effect? Ecological Economics 2001;36:119–32.
[25] Greene DL, Kahn JR, Gibson RC. Fuel economy rebound Effect for U.S. household vehicles. The Energy Journal 1999;20(3):1–31.
[26] Sorrell S, Dimitropoulos J, Sommerville M. Empirical estimates of the direct rebound effect: A review. Energy Policy 2009;37:1356–71.
[27] Frondel M, Peters J, Vance C. Identifying the rebound: evidence from a German household panel. The Energy Journal 2008;29:145–63.
[28] Brandt L, Holz CA. Spatial price differences in China: estimates and implications. Economic Development and Cultural Change 2006;55(1):43–86.
[29] Thom HC. Seasonal degree day statistics for the United States. Monthly Weather Review 1952;80(2):143–9.
[30] Kadioglu M, Zekai S. Degree-day formulations and application in Turkey. Journal of Applied Meteorology 1999;38(6):837–46.
[31] Sailor DJ. Relating residential and commercial sector electricity loads to climate-evaluating state level sensitivities and vulnerabilities. Energy 2001;26:645–57.
[32] Dargay JM. Are Price & Income Elasticities of Demand Constant? The UK Experience Oxford, UK: Oxford Institute for Energy Studies; 1992.
[33] Gately D. The imperfect price reversibility of world oil demand. Energy Journal 1993;14(4):163–82.
[34] Bilgili F, Pamuk Y, Tülüce NSH. Short run and long run dynamics of residential electricity consumption:homogeneous and heterogeneous panel estimations for OECD. Economic Computation and Economic Cybernetics Studies and Research 2011;3:113–26.
[35] Kao C. Spurious regression and residual-based tests for cointegration in panel data. Journal of Econometrics 1999;90:1–44.
[36] Liang YF, Gao TM. Empirical analysis on real estate price fluctuation in different provinces of china. Economic Research Journal 2007;8:133–42.
[37] Hausman J. Specification tests in econometrics. Econometrics 1978;46:1251–71.
[38] Wooldridge JM. Introductory econometrics: a modern approach. Beijing: China Ren-min University Press; 2007 ([in Chinese]).
[39] Hass R, Schipper L. Residential energy demand in OECD-countries and the role of irreversible efficiency improvements. Energy Economics 1998;20(4):421–42.
[40] Dargay JM, Gately D. The imperfect price irreversibility of non-transportation of all demand in the OECD. Energy Economics 1995;17(1):59–71.
[41] Wang ZH, Zhang B, Zhang YX. Determinants of public acceptance of tiered electricity price reform in China: evidence from four urban cities. Applied Energy 2012;91:235–42.